



THE UNIVERSITY *of* EDINBURGH

Edinburgh Research Explorer

Designing for tapers and defects in FRP-strengthened metallic structures

Citation for published version:

Stratford, TJ & Chen, J-F 2005, Designing for tapers and defects in FRP-strengthened metallic structures. in JF Chen & JG Teng (eds), *Bond Behaviour of FRP in Structures: Proceedings of the International Symposium BBFS 2005*. IIFC SECRETARIAT, HONG KONG, pp. 453-458, International Symposium on Bond Behaviour of FRP in Structures, Hong Kong, 7/12/05.

Link:

[Link to publication record in Edinburgh Research Explorer](#)

Document Version:

Publisher's PDF, also known as Version of record

Published In:

Bond Behaviour of FRP in Structures: Proceedings of the International Symposium BBFS 2005

General rights

Copyright for the publications made accessible via the Edinburgh Research Explorer is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The University of Edinburgh has made every reasonable effort to ensure that Edinburgh Research Explorer content complies with UK legislation. If you believe that the public display of this file breaches copyright please contact openaccess@ed.ac.uk providing details, and we will remove access to the work immediately and investigate your claim.



DESIGNING FOR TAPERS AND DEFECTS IN FRP-STRENGTHENED METALLIC STRUCTURES

T. J. Stratford and J. F. Chen

Institute for Infrastructure and Environment, The University of Edinburgh, UK.

Email: Tim.Stratford@ed.ac.uk, J.F.Chen@ed.ac.uk.

ABSTRACT

Adhesively bonded FRP strengthening for metallic structures relies critically on the adhesive joint between the FRP and the metal. Current best-practice in design allows the distribution of shear and peel stress along the adhesive connection to be determined, which are compared to the strength of the adhesive joint. This paper considers how this technique can be applied to (a) design stress reduction measures such as tapers, stepped plates and clamps; and (b) assess the significance of defects within the adhesive layer.

KEYWORDS

FRP, metallic structures, steel, strengthening, interfacial stresses, tapers, defects.

INTRODUCTION

Externally-bonded FRP strengthening is an increasingly economic method of rehabilitating *metallic* infrastructure. The first applications increased the flexural load capacity of cast iron bridges in the UK (1996). The technique has since been applied to numerous cast iron and steel structures, and its potential applications include fatigue-life extension, increased buckling capacity, and prestressed strengthening. Two UK design guides have been produced for this rapidly developing strengthening method (Moy 2001; Cadei *et al.* 2004).

Like FRP strengthened concrete, FRP strengthened metals rely on interfacial bond to transfer load into the strengthening material and the system must be designed to carry the required bond stresses. However, a properly implemented FRP-metal adhesive connection fails adhesively (compared to failure within a concrete substrate); thicker FRP plates are often required when strengthening metallic structures, resulting particularly in greater adhesive peel stresses; and the joint is susceptible to installation defects.

The designer of an FRP strengthening scheme for a metallic structure requires analytical tools that (i) allow the adhesive stresses to be predicted and compared to the adhesive joint's strength, (ii) give the designer options for reducing these stresses, and (iii) allow the significance of defects to be assessed.

INTERFACIAL STRESS ANALYSIS FOR DESIGN

The aim of the interfacial stress analysis is to predict the shear (τ) and through-thickness peel (σ) stress distributions within the adhesive joint. Current best-practice for the design of FRP-strengthening for metallic structures uses a low-order linear-elastic stress analysis (Cadei *et al.*, 2004). Many low-order stress analyses are available, which differ in detail but are essentially similar (e.g. Smith and Teng 2001, Deng *et al.* 2004, Stratford and Cadei 2006). These do not strictly satisfy the zero shear boundary condition at the end of the adhesive, which requires a high-order analysis (e.g.: Yang *et al.* 2004); however, the complexity of high-order analyses prohibits their use in design. Low-order analyses implicitly rely on stress redistribution within the adhesive, but this is localised.

Current design of FRP strengthening for metallic structures in civil engineering uses linear-elastic analysis, even though elasto-plastic analysis has been successfully used to design bonded-FRP patches for aluminium aerospace skins (Davis and Bond 1999). Civil engineering strengthening generally requires thicker sections of FRP than aerospace applications, resulting in far greater peel stresses (Hutchinson and Hurley 2001), for which adhesives are brittle (Kinloch 1997).

Fracture mechanics methods have yet to transfer to civil engineering strengthening applications, largely due to the difficulty of characterising mixed-mode (shear-peel) behaviour (Buyukozturk *et al.* 2003).

It is not the intention of this paper to present a further low-order bond stress analysis, but to explore how they are used in design. The focus of the paper is on the adhesive stress concentration at the end of a strengthening plate, and not upon the adhesive stresses due to yielding of the substrate or in the vicinity of a fatigue crack (although similar techniques apply). The following examples were produced using the analysis developed for CIRIA report C595 (Cadei *et al.* 2004, Stratford and Cadei 2006).

Typical Results

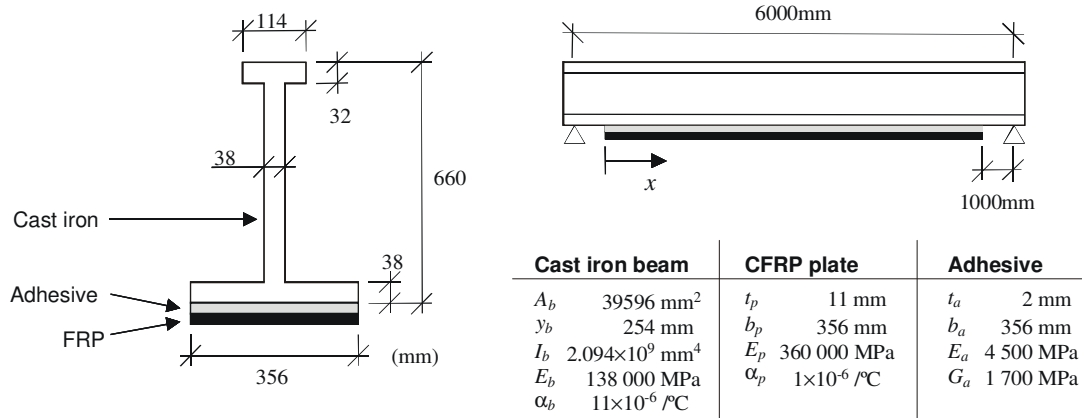


Figure 1 Details of the strengthened cast iron beam considered in the examples

Figure 1 shows a cast iron beam strengthened in flexure using an 11mm thick UHM CFRP plate (based upon a typical bridge strengthening project in the UK). Figure 2 plots the shear (τ) and peel (σ) stresses predicted for significant load cases:

1. A distributed applied load of 40 kN/m (required by modern traffic loading) results in maximum adhesive stresses of $\tau=4.2$ MPa and $\sigma=2.5$ MPa.
2. A temperature change of 30°C generates locked-in stresses due to differential thermal expansion between the cast iron and the CFRP. The maximum stresses are $\tau=13.8$ MPa and $\sigma=7.9$ MPa.
3. The combination of applied load and temperature change gives $\tau=18.0$ MPa and $\sigma=10.4$ MPa.
4. If the CFRP plate is prestressed to a strain of 0.05%, transfer of the prestress gives $\tau=23$ MPa and $\sigma=13$ MPa.

The adhesive stresses resulting from differential thermal expansion are particularly significant. If the strengthening is applied during the winter at 15°C, the temperature could easily rise to 45°C during the summer (e.g. Highways Agency 2001). The resulting adhesive stresses are far greater than those due to the applied load.

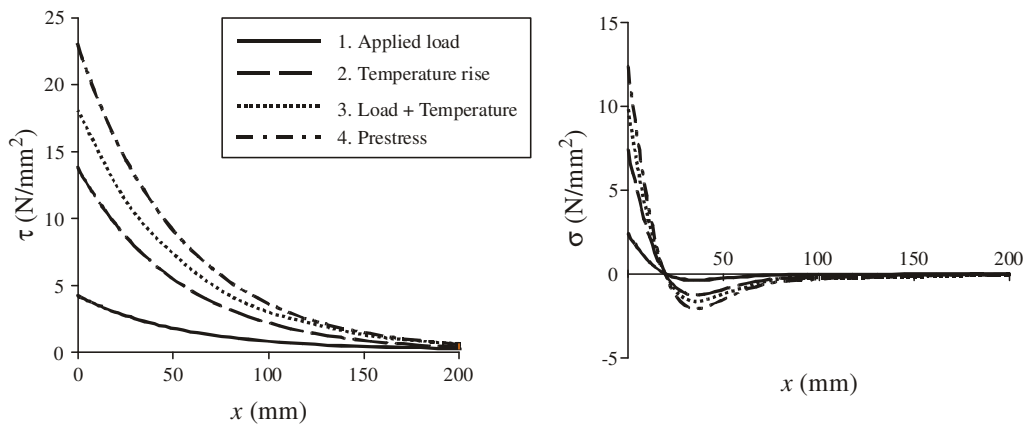


Figure 2 Adhesive stresses due to applied load, temperature change, and transfer of prestress

Having determined the adhesive stresses, these must be compared to the strength of the adhesive joint. The strength is usually determined using lap-shear tests (ASTM 2001, BSI 2002), but these tests must be back-

analysed using a consistent method to determine the *peak* adhesive stresses at failure (e.g. Goland and Reissner 1944).

REDUCING THE PEAK ADHESIVE STRESS THROUGH DETAILING

If the designer establishes that large stresses are present within an adhesive joint, the designer must find a way to accommodate them. One option is to seek a higher strength joint by using a different adhesive; however, this is rarely possible due to the greater demands on the quality of surface preparation prior to bonding. Alternatively, the designer can modify the geometry of the strengthening and adhesive close to the end of the plate to reduce the maximum adhesive stresses.

It is well known that a *spew fillet* of adhesive should be left around the edge of FRP strengthening because it reduces the adhesive stress concentration (Frostig *et al.* 1999). For example, a finite element analysis of three different fillet geometries (figure 3) shows that a spew fillet reduces the peak adhesive stresses by approximately 25%. The concave fillet geometry is probably the most realistic, due to the possibility of adhesive shrinkage as it cures. However, a *spew fillet cannot be relied upon for design purposes* because the fillet is very vulnerable to environmental attack, and can easily become chipped or otherwise damaged.

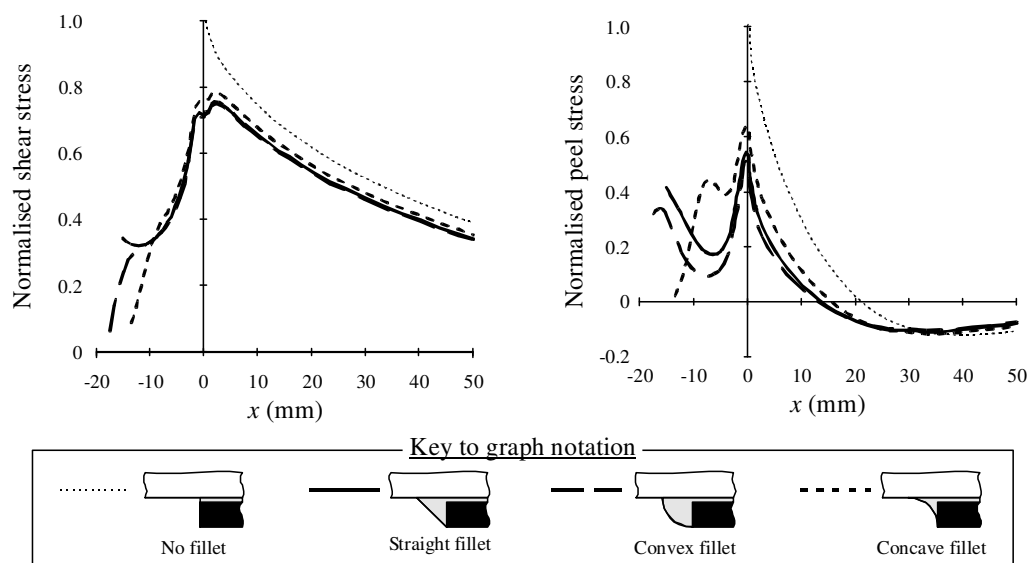


Figure 3 Adhesive stresses variation for different spew fillet geometries (Clarke and Douglas 2003)
(Normalised by the maximum adhesive stress without a fillet)

Modifying the geometry of the *strengthening plate* is a far more robust method for reducing the adhesive stress concentration, and a low-order analysis can be used to predict the bond stress in these cases (Deng *et al.* 2004, Stratford and Cadei 2006):

- *Stepped strengthening plates* (Figure 4) give approximately 20% reduction in adhesive stress. Note that it is important to check the adhesive joint between the two plates in this case.
- *Tapered strengthening* (Figure 5) reduces the maximum shear stress by 25% and the peel stress by 50% (approximately).
- A *reverse taper* (in which the adhesive thickness increases as the plate thickness reduces) is by far the most effective method for reducing adhesive stress, as is well known in the aerospace industry. This gives a reduction in shear stress of 50% and in peel stress by 75% (approximately). Reverse tapers are rarely used in civil engineering applications, however, due to the perceived difficulty of fabrication.

Where modifying the geometry of the strengthening plate does not reduce the adhesive stresses sufficiently, mechanical clamps can be used to react the adhesive stresses (for example, at the end of prestressed strengthening). Figure 6 shows the compressive normal stress distribution for a 10kN clamping force, which reduces the peel stresses, and hence increases the capacity of the connection.

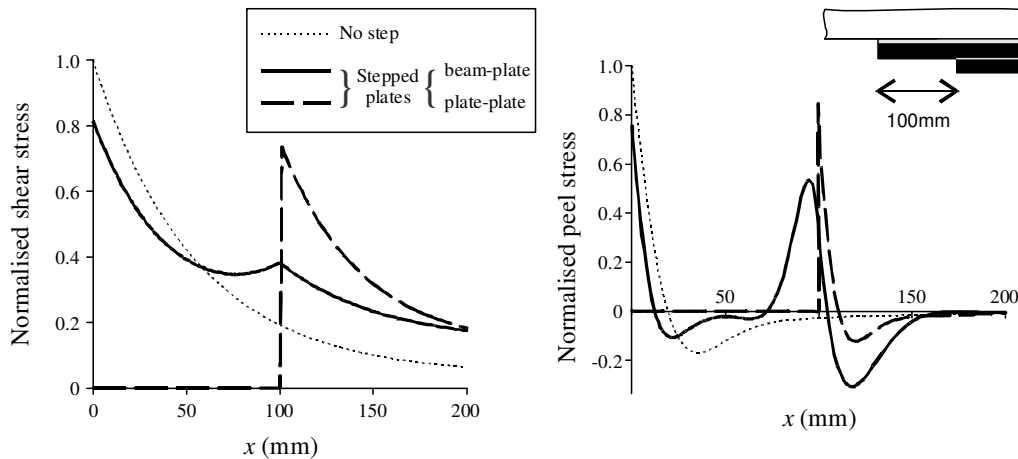


Figure 4 Reduction in adhesive stresses by using stepped plates
(Normalised by the maximum adhesive stress without a step)

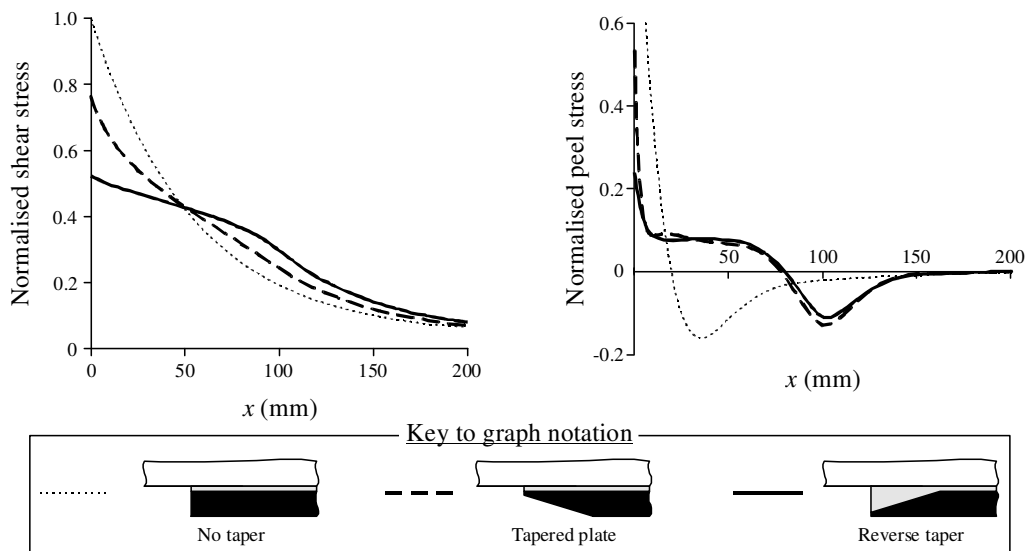


Figure 5 Reduction in adhesive stresses using two different forms of taper
(Normalised by the maximum adhesive stress without tapering)

EFFECT OF DEFECTS ON INTERFACIAL BOND STRESSES

Strengthening projects are carried out on construction sites, which are very different to the laboratory conditions or a factory production line. Whilst the working environment is controlled to facilitate the strengthening work, the possibility of defects in the adhesive layer must always be considered. The specification should specify acceptable defect sizes, and if defects are discovered during a periodic inspection they must be assessed to determine their significance.

Tap-testing is generally used to detect adhesive defects on construction sites. Figure 7 shows a typical voided area in an FRP-concrete adhesive joint detected using this method. NDT methods such as ultrasonic inspection (Bastianini *et al.* 2004) or infrared thermography can also be used. No inspection technique can currently detect all types of defect (for example, touching dis-bonds are very difficult to detect), and the minimum detectable defect size is around 10mm (depending upon the thickness of strengthening). Figure 8 shows an infrared image for a FRP-steel adhesive joint containing known defects.

An adhesive stress analysis can be used to assess the significance of simple defects. For example, Figure 9 shows a large defect: a 50mm long lack of bond, 10mm from the end of strengthening with a reverse taper

which might be due to poor surface preparation. The defect results in a 40% increase in the peak adhesive shear stress, probably leading to failure of the adhesive joint.

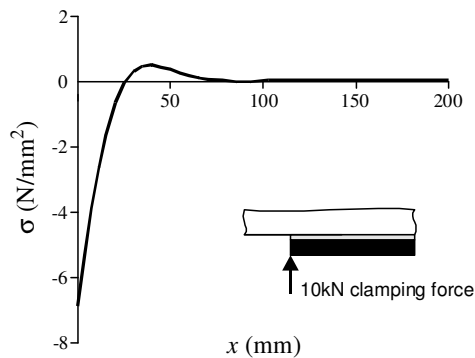


Figure 6 Peel stresses due to a 10kN clamping force



Figure 7 A typical defect area, found by tap testing (FRP applied to concrete)

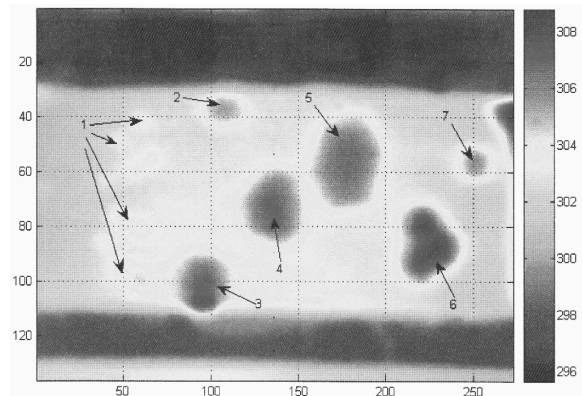
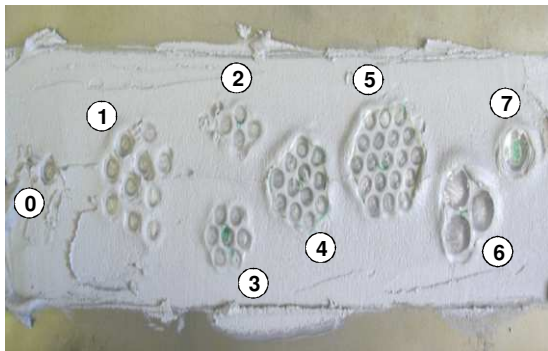


Figure 8 Infrared thermography detection of voids within an FRP-metal adhesive joint (Bai 2005)
(Bubble size \approx 10mm, except for defects 6 & 7)

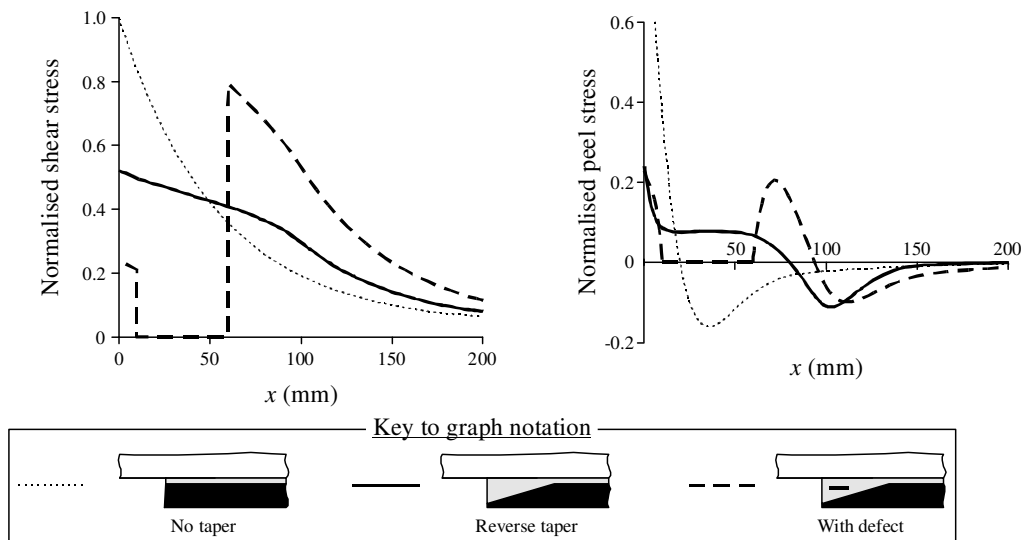


Figure 9 The effect of a workmanship defect on the adhesive stresses with a tapered plate

Defects in the adhesive at the end of a strengthening plate are particularly detrimental. This zone is most highly stressed, and it is also exposed to environmental attack and other forms of damage. The stability a crack propagating in the end of the adhesive should be assessed, particularly where the strengthening has been tapered to reduce the stress concentration. Figure 10 shows how the peak adhesive stresses grow as an end defect propagates into the length of tapered and reverse tapered plates.

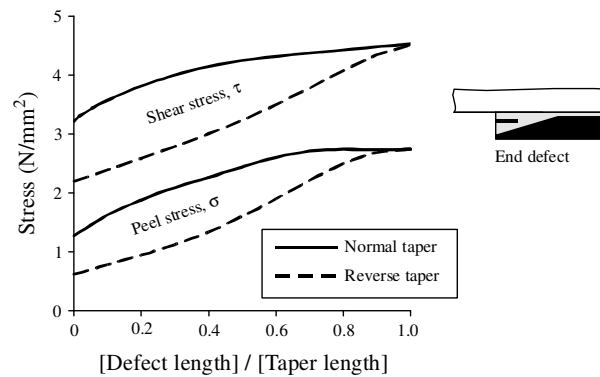


Figure 10 Increase in adhesive stresses due to an end defect

CONCLUSIONS

A low-order linear-elastic adhesive stress analyses is a powerful tool for designing bonded FRP strengthening for metallic structures, and the method is current best-practice for the design of square-ended strengthening. This paper has shown how the analysis can be used to analyse stress reduction measures, such as tapers, stepped plates, and clamps. The technique also provides a tool for assessing the significance of simple bond defects.

REFERENCES

- ASTM (2001). "Standard Test Method for Lap Shear Adhesion for Fiber Reinforced Plastic (FRP) Bonding", ASTM D5868-01, ASTM International.
- Bastianini, F., Ceriolo, L., Di Tommaso, A. and Zaffaroni, G. (2004). "Mechanical and Nondestructive Testing to Verify the Effectiveness of Composite Strengthening on Historical Cast Iron Bridge in Venice Italy", *Journal of Materials in Civil Engineering*, ASCE, 16(5), 407-413.
- BSI (2002). "Methods of test for adhesives: Determination of bond strength in longitudinal shear for rigid adherends", BS 5350-C5:2002, British Standards Institute.
- Buyukozturk, O., Gunes, O. and Karaca, E. (2003). "Progress on understanding debonding problems in reinforced concrete and steel members strengthened using FRP composites", *Construction and building materials*; 18, 9-19.
- Cadei, J.M.C., Stratford, T.J., Hollaway, L.C. and Duckett, W.G. (2004). *C595 - Strengthening metallic structures using externally-bonded fibre-reinforced-polymers*. CIRIA, London.
- Clarke, M. and Douglas, C. (2003). *Temperature Effects on FRP Strengthened Metallic Members*, MEng theses, School of Engineering and Electronics, The University of Edinburgh.
- Davis, M. and Bond, D. (1999). "Principles and practices of adhesive bonded structural joints and repairs", *International Journal of Adhesion and Adhesives*, 19, 91-105.
- Deng, J., Lee, M.M.K. and Moy, S.S.J. (2004). "Stress analysis of steel beams reinforced with a bonded CFRP plate". *Composite Structures*, 65, 205-215.
- Bai, Y. (2005). *Applications of NDT Techniques for the Evaluation of the condition of the bond between FRP and Steel*, MEng thesis, School of Engineering and Electronics, The University of Edinburgh.
- Frostig, Y., Thomsen, O.T. and Mortensen, F. (1999). "Analysis of adhesive-bonded joints, square-end, and spew-fillet – high-order theory approach", *Journal of Engineering Mechanics*, 125(11), 1298-1307.
- Goland, M. and Reissner, E. (1944). "The Stresses in Cemented Joints", *Journal of Applied Mechanics, Transactions of ASME*, 11, A11-27.
- Highways Agency (2001). *Loads for Highway Bridges*, BD 37/01, The Highways Agency, London.
- Hutchinson, A.R. and Hurley, S.A. (2001). *Transfer of Adhesives Technology – Feasibility Study*, Project Report 84, CIRIA, London, 96pp.
- Kinloch, A.J. (1997). "Adhesive in Engineering", *Proc. Instn. Mech Engrs*, 211 Part G, 307-335.
- Moy, S.S.J. (ed) (2001). *FRP composites – Life Extension and Strengthening of Metallic Structures*. Institution of Civil Engineers, London, 64pp.
- Smith, S.T. and Teng, J.G. (2001). "Interfacial stresses in plated beams", *Engineering structures*, 23, 857-871.
- Stratford, T.J. and Cadei, J.M.C. (2006). "Elastic Analysis of Adhesion Stresses for the Design of a Strengthening Plate Bonded to a Beam", *Construction and Building Materials*, 20, 34-45.
- Yang, J., Teng, J.G. and Chen, J.F. (2004). "Interfacial stresses in soffit-plated reinforced concrete beams." *Proc Inst Civil Engineers: Structures and buildings*, 157(1), 77-89.